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HEAT AND MASS TRANSFER AND PHYSICAL GASDYNAMICS

Effectiveness of Steam Generation in Oxyhydrogen Steam Generators of the Megawatt Power Class

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Abstract—Findings of experimental investigations and optimization of the processes of mixture formation, combustion, and steam generation in experimental H_2/O_2 steam generators of the megawatt power class are presented.

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INTRODUCTION

Investigations and developments of oxyhydrogen steam generators were initiated by theoretical investigations carried out in the late 70s and early 1980s in the Soviet Union [1], the United States [2], and Germany [3]. In these and follow-up papers [4–19], the creation of hydrogen systems accumulation and production of thermal and electric energy is shown. In the hours with the load minimum, hydrogen and oxygen are produced by water electrolysis, fed into storage, and used in hours of peak load for the production of additional power by hydrogen combustion in oxygen and the additional superheating of steam and an increase in its flow rate before the mean- and/or low-pressure cylinder of a turbine [5, 6].

A basic new element of hydrogen systems for electric power accumulation and compensation of load curve unevenness (first of all, in production of peak and subpeak power) on NPPs and SPPs is the high-pressure oxyhydrogen steam generator of the megawatt power class. Investigations of processes and developments of this new technique were carried out by the Germany aerospace center (DLR) [8, 12–14] and the Joint Institute for High Temperatures (JIHT), Russian Academy of Sciences, in cooperation with the Public Company Chemical Automatic Design Bureau (CADB) [17–22]. In Japan, investigations of processes in oxyhydrogen steam generators were carried out under a WE-NET program on models of the kilowatt power class [23–26]. The developments of H_2/O_2 steam generators used the experience of rocket (liquid-propellant rocket engines, LREs) and aviation (gas-turbine engines, GTEs) technologies. The generalized schematic of the H_2/O_2 steam generator based on LRE technologies is represented in Fig. 1.

The development of these sets is connected with solving the following scientific and technical problems.

(i) There is a need to provide for effective mixing of the components and the most complete hydrogen combustion in oxygen at high pressure and a ratio close to stoichiometric for their flow rates at the inlet into the combustion chamber (CC). The admissible content of unburnt unconcentrated gases at the outlet of a flame unit must be no more than 2 vol %. At the same time, the completeness of hydrogen combustion in the CC at high pressures is limited by the cutting of combustion reaction chains due to the active particle death as a result of triple collisions and at cooled walls of the CC and by a number of other mechanisms [27, 28]. In addition, as a result of hydrodynamic and thermal processes within the CC, the combustion zone can be fed by the excess flow of its product, namely, steam, which results in a shift reaction in the direction of the starting components, i.e., in incomplete combustion of hydrogen unburning. Such an effect, as is shown in [24, 25, 29], may be caused by cooling the CC walls by the steam feed, the steam feed into the combustion zone along with fuel components, or the excess water feed into the CC. These effects are especially substantial for fuel–oxidizer compositions closed to the stoichiometric composition.

(ii) The provision for the stable operation of the flame unit under extreme thermal loads on its elements applies additional and sometimes very rigid requirements on the CC wall cooling system, particularly during steam generator operation in partial modes. Because the entire CC wall cooling component (water) mixes with combustion products and decreases their temperature, its flow rate is determined by the desired parameters of the steam at the steam generator outlet and must decrease as the power reduces, which can result in the appearance of boiling

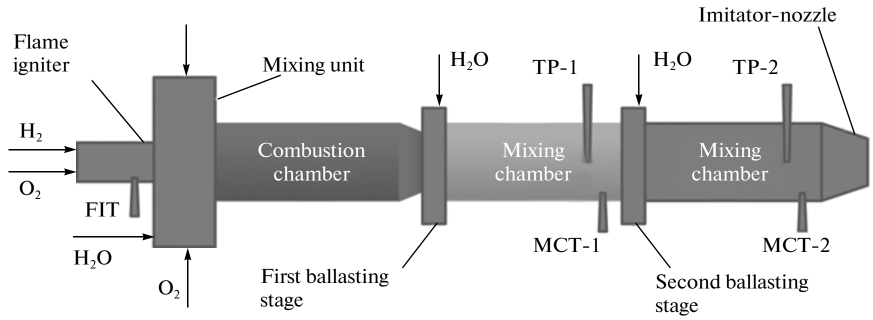

Fig. 1. Generalized schematic of the flame unit of the experimental oxyhydrogen steam generator of the JIHT with a thermal power up to 25 MW: FIT pressure transducer in the flame igniter; MCT-1, MCT-2 pressure transducers in mixing chambers of the first and second ballasting stages; TP1, TP2 temperature pick-ups in mixing chambers of the first and second ballasting stages.

and a heat exchange gap in the external cooling system of the CC [12].

(iii) The high molecular diffusion rate in oxyhydrogen mixtures and wide ignition ranges result in the situation wher the front of active diffusion combustion in the CC lies closer to the injector head than in cases of other fuels. This leads to great thermal loads of the flame wall of the CC. Processes of component mixing and turbulent combustion in the CC can be accompanied by the appearance of reverse-direction vortices of hot oxygen-enriched gases capable of active oxidation of metal of the CC and its destruction at the contact with the hot flame wall. The structure of the mixing top of the CC and the arrangement of injectors must provide for the elimination of such processes.

(iv) Finally, it should be noted that the possibility for the analysis and calculation of processes in apparatuses of various sizes (thermal power classes) on the basis of the hydrodynamic and thermal similarity of processes in the CC and for the use of results of experiments with the H_2/O_2 steam generators of the kilowatt power class is very limited in the development of apparatuses of the megawatt power class.

The current paper represented findings of experimental investigations directed to solving these problems and the development of oxyhydrogen steam generators of the megawatt power class.

TECHNIQUE OF EXPERIMENTAL INVESTIGATIONS

In the preceding step of developments, the JIHT produced an experimental H_2/O_2 steam generator of the 10M model with a thermal power to 18 MW, which operated on hydrogen gas and liquid oxygen with a mixing unit with the coaxial-jets injectors providing under these conditions for the good mixing of components and the completeness of hydrogen combustion, and a H_2/O_2 steam generator of the 20K model with a thermal power to 20–100 kW which operated by the gas–gas fueling scheme [20, 21]. In the future, the operation on gaseous components of hydrogen and oxygen is required to pass to mixing units with impinging jets, which provided in this case for the best mixing at the minimum length of the combustion chamber and to a two-stage scheme for the feed of a ballasting component, namely, water, into the evaporating and mixing chamber. These investigations were carried out with an experimental H_2/O_2 steam generator of the 25M model with a thermal power to 25 MW which operated by the gas–gas fueling scheme [22, 30]. The calculated parameters of the experimental steam generator are listed in Table 1, and its outward appearance on an experimental test bench CADB is represented in Fig. 2.

The combustion unit of the experimental oxyhydrogen steam generator [30] consists of the following basic elements (Fig. 1).

(i) The flame igniter (FI) presenting a low-consumption prechamber with electric-spark ignition initiation for the mixture operating on the same fuel components as the basic set, namely, on the oxygen and hydrogen gases. It produces the pilot flame realizing fuel ignition in the combustion chamber of the combustion unit [31].

(ii) The mixing unit (flame wall of the CC) containing injectors for the fuel component feed and injectors for the water feed for the curtain cooling of the CC [30, 32]. Experimental investigations were carried out with the developed and made mixing units (MU) of four types of the JIHT design with various geometrical characteristics and types of injectors, namely, with the jet injectors with the hydrogen and oxygen jet impinging under the angle θ, with the jet injectors with the hydrogen and oxygen jet impinging under the angle θ/2, and reduced diameters of oxygen injectors, with the jet injectors with the hydrogen and oxygen jet impinging under the angle θ/2 and additional peripheral hydrogen injectors, and injectors of the CADB design with the coaxial injectors of a special configuration [33].

(iii) The combustion chamber presenting a cylinder with 295 mm length and 80 mm inner diameter with cooled walls and a converging nozzle at the outlet which provides for more complete mixing of combustion products with the ballasting water. This element is

Table 1. Design parameters of the experimental oxyhydrogen steam generator of the 25M model

Designed thermal power, MW	Oxygen gas flow consumption, g/s	Hydrogen gas flow consumption, g/s	Cooling water flow consumption, kg/s	Steam temperature at the outlet, K	Pressure in the combustion chamber, MPa
15–25	960–1600	120–200	1.5–4	up to 1400	up to 7.5

the most calorific intensive (heat fluxes in the wall amount up to 15 MW/m^2) and to a greater extent affects the life time and the reliability of the entire set operation. The combustion chamber consists of a flue tube (of the grade BrKh-08 bronze) mounted in a strong steel casing and cooled by the external convective water flow in channels and the cooling system with the irrigation of the internal surface by ballasting water. Water feeds from the external cooling system into an evaporation chamber, and the water film formed by irrigation at the internal surface evaporates practically completely in the CC. The division of flows of cooling water into internal and external ones provides for the absence of excess water and steam in the CC and the attainment of maximum completeness of hydrogen combustion.

(iv) The evaporation chamber in which combustion products mix with ballasting water and evaporate it. The flame unit of the oxyhydrogen steam generator contains two sections of the evaporation chamber and two stages for the feed of ballasting water which allows for changing the distribution of the concentration of the liquid phase over the chamber length for eliminating the effects of quenching the composition and for attaining a uniform steam temperature at the outlet. The engineering solutions of basic elements and the

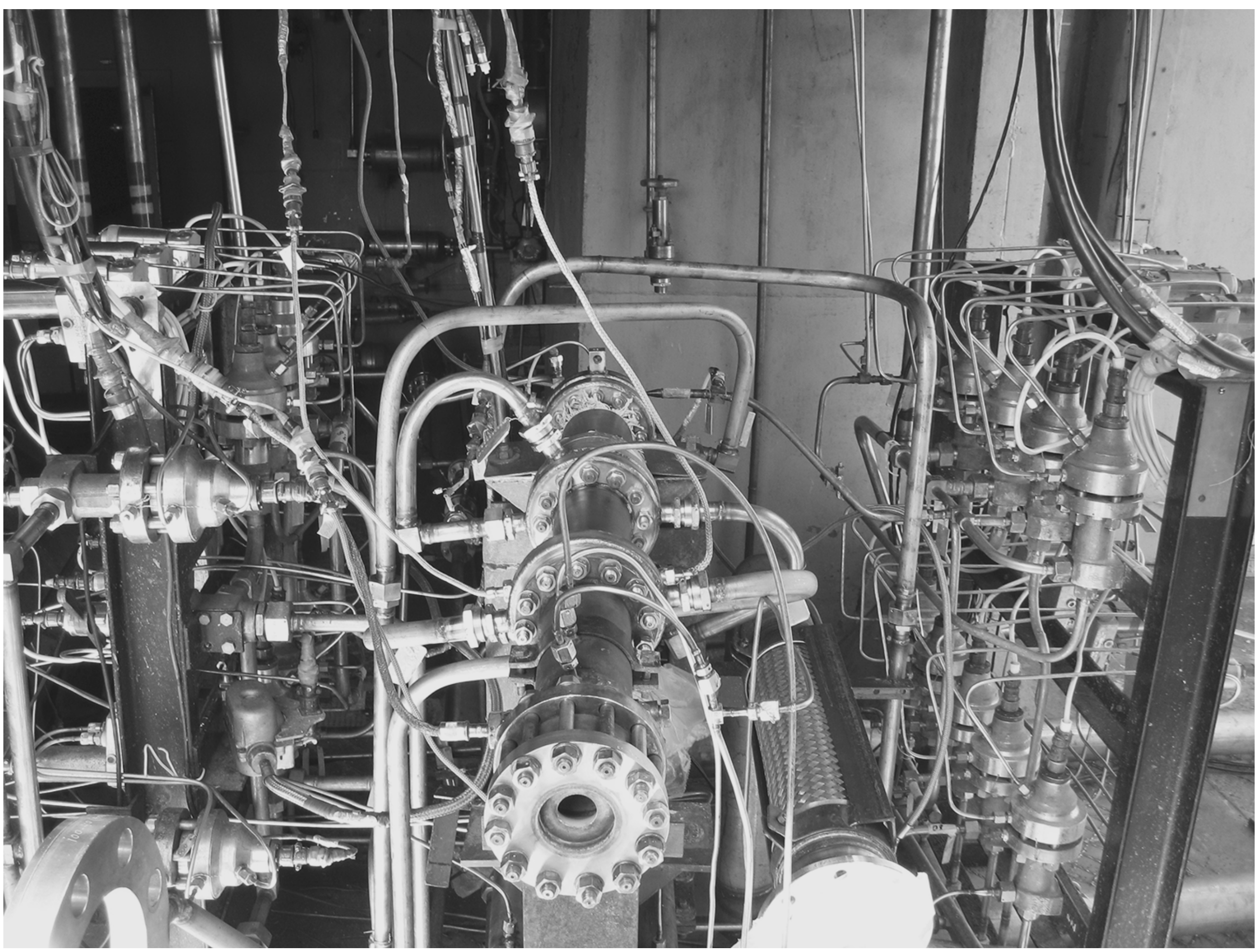

Fig. 2. Appearance of the oxyhydrogen steam generator with a thermal power up to 25 MW at the experimental test bench of the CADB.

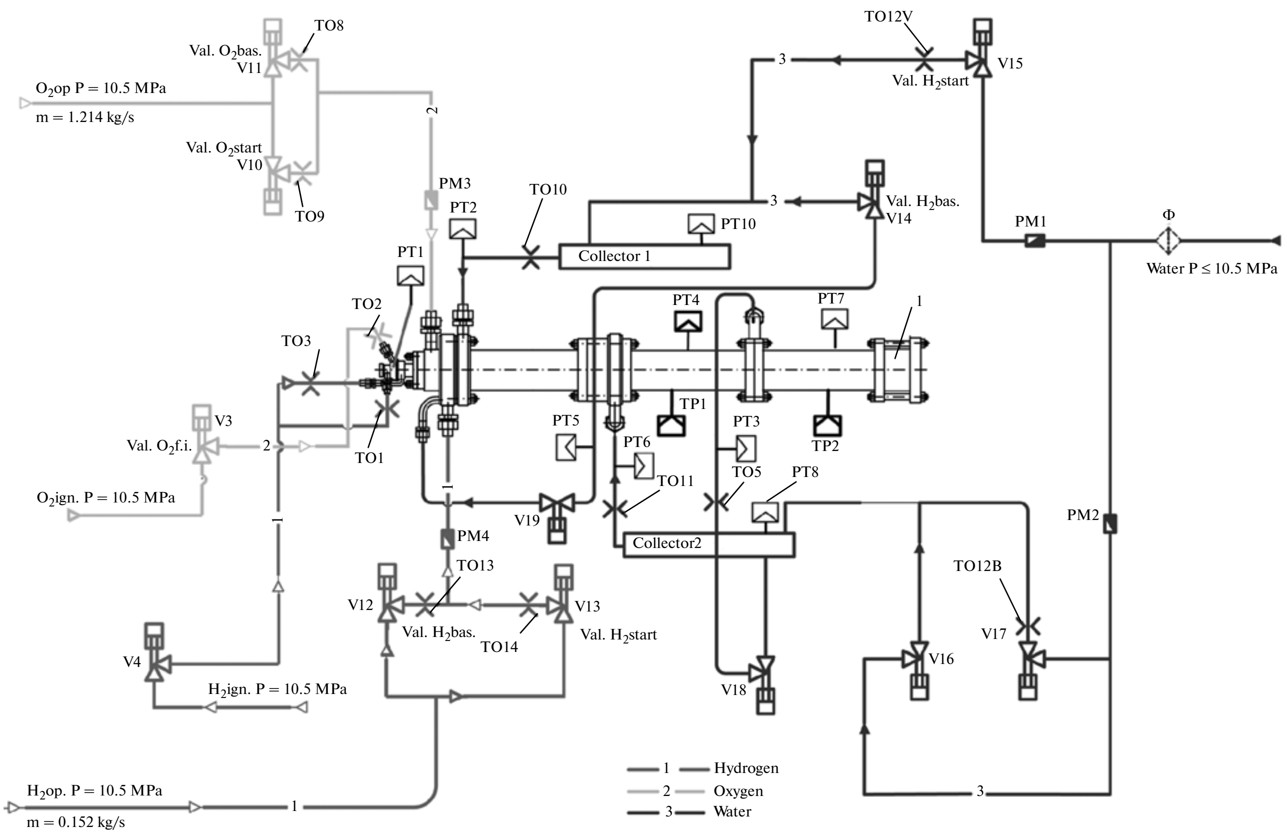

Fig. 3. Schematic of the diagnosis and feed of basic components of the experimental unit of the oxyhydrogen steam generator: PT1–PT10 pressure transducers; TP1, TP2 temperature pick-ups; V1–V19 electro-pneumatic valves; TO1–TO14 throttling orifices.

steam generator as a whole are protected by RF patents [30–32].

The overall dimensions of the experimental steam generator with thermal power up to 25 MW are the following: external diameter is 270 mm; and total length, 1270 mm.

Experimental investigations of processes were carried out at the feed of basic components into the combustion unit of the experimental steam generator by two stages that corresponded to two operation modes (starting and basic) providing for the more continuous operation of the set and eliminating the abrupt pressure gradients within the combustion unit. Physically, two modes were provided by the mounting of two electro-pneumatic valves for each component (Fig. 3) and their successive opening and closing in accordance with the developed sequence diagram of experiments.

Starting of the experimental oxyhydrogen steam generator and going into the basic mode occur in accordance with the developed sequence diagram (Fig. 4): at first, hydrogen and oxygen are fed into the flame igniter, and the initial flame ignition occurs by an electric spark-plug; further, the starting hydrogen and oxygen valves open. The components feed into the CC and ignite. Simultaneously, the starting water discharges for cooling the combustion chamber and ballasting feeds. After that, the FI operates in the mode of ventilation and cooling by hydrogen. The steam generator outlet is equipped with an imitator-nozzle for the formation of the desired pressure within the oxyhydrogen steam generator. Experimental investigations were carried out on the test bench of the test complex of the CADB.

The general characteristics of the oxyhydrogen steam generator are the output parameters of steam. Particularly, the unevenness of the temperature field must be no greater than 40 K along the radius. It is also necessary to minimize vibration loads, and the total content of unburnt components (of fuel and oxidizer) at the outlet must be no more that 2 vol%. The basic parameters of processes were controlled by temperature pick-ups with four thermocouples (TP1 and TP2 in Fig. 3) determining the temperature of steam along the radius from the center to the wall of the CC. Thus, the unevenness of the temperature field was recorded.

Because determination of small concentrations of unburnt components of hydrogen and oxygen in the high-temperature steam is difficult with high accuracy during the operating process in the CC, the experiment was accompanied by steam extraction according to a scheme shown in Fig. 5. Further, the greater part

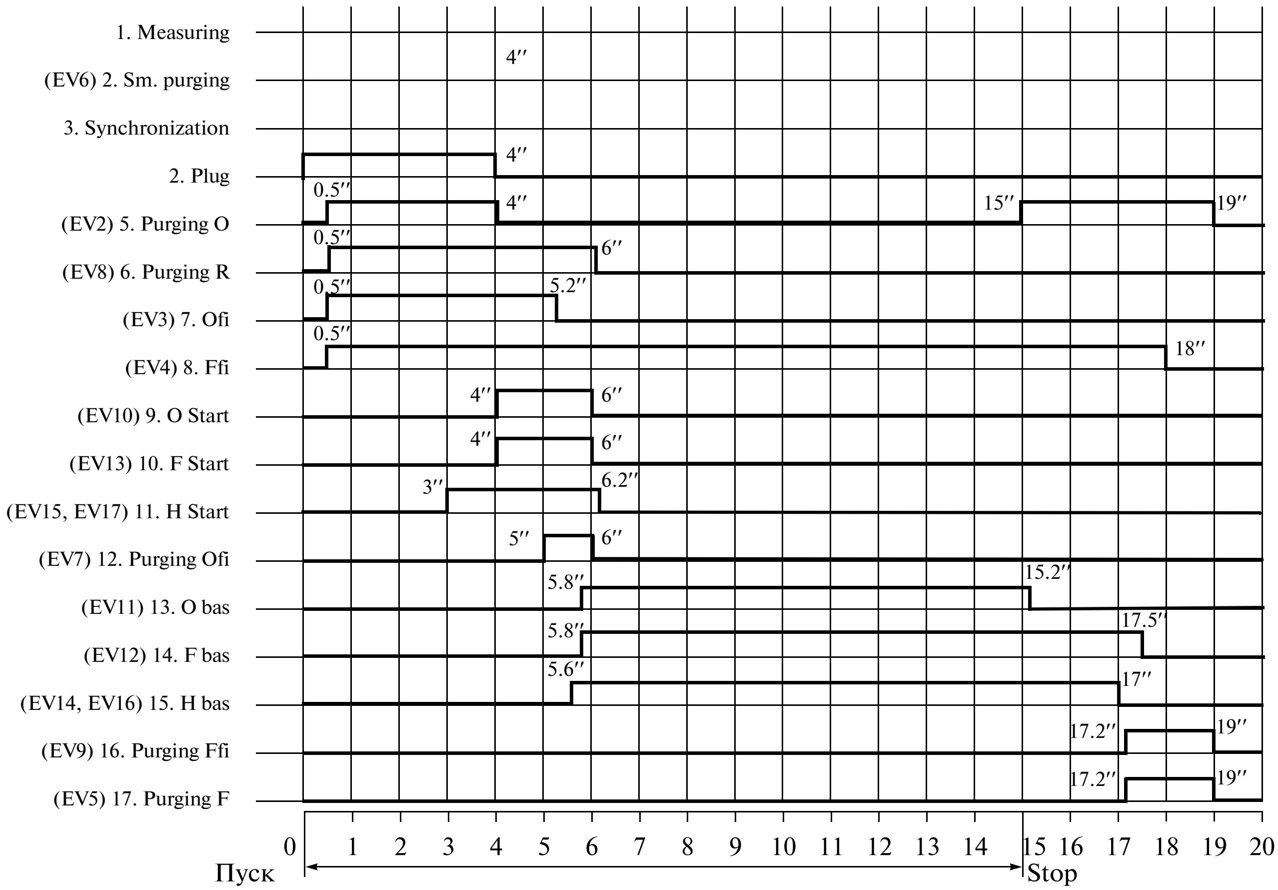

Fig. 4. Sequence diagram of start and standby of the experimental oxyhydrogen steam generator.

of steam was condensed within a condenser and drained into a condensate tank, and the residual noncondensed components mixed with helium and were fed into a control tank after which chromatography analysis of the mixture composition in the control tank and determination of the concentration of unburnt components in steam were fulfilled. The extraction was carried out in the basic operation mode of the oxyhydrogen steam generator for 4 s.

THERMAL PROCESSES IN THE COMBUSTION CHAMBER

The results of design simulation and experimental investigations allow us to make a number of conclusions on the character of thermal processes in H_2/O_2 steam generators. By analogy with the LRE, the combustion chamber of the hydrogen steam generator (HSG) schematically can be conditionally zoned.

(i) Zone of the mixing and combustion of fuel in the flow core. The jet mixing units are characterized by the diffusiveness of the combustion front because mixing and combustion occur simultaneously. The front position and the extension of the zone x_0 depend on the velocity and the angles of the incidence and divergence of the fuel and oxidizer jets, i.e., determined by the design of the injector head and the diameter of the CC.

(ii) Zone of mixing the combustion products in the flow core. In this zone the smoothing of large-scale heterogeneities of the temperature and composition of combustion products occurs.

(iii) Zone of heating the liquid curtain at the walls of the CC and its evaporation. The extension of this zone is determined by heating the liquid in the film to the saturation temperature at pressure in the CC and by its evaporation due to convective and radiant heat fluxes and depends on the mass flow rate of the liquid for the curtain, thermal load of the walls of the CC, gas velocity, and a number of other factors.

(iv) Zone of the mixing of gas from the flow core with steam from the curtain. The irregularity of the partial pressures of combustion products, steam from the curtain, and the unreacted fuel and oxidizer along the radius of the CC reduces, and the gas composition is settled at the CC outlet.

(v) Zone of the gaseous curtain. The liquid film at the CC walls at the origin of this zone evaporates completely, and the wall layer is formed by the superheated steam heated owing to the convective and radiant heat fluxes.

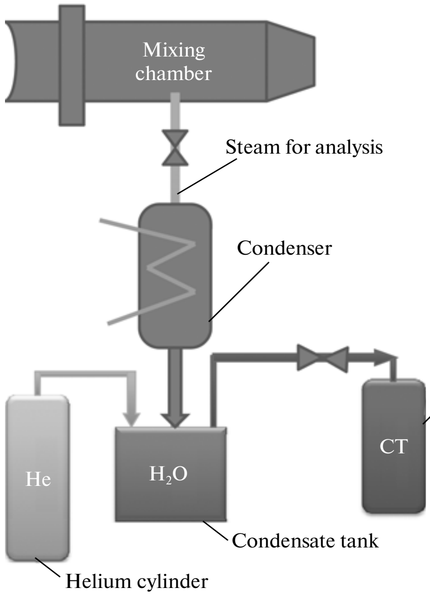

Fig. 5. Schematic of steam extraction from the oxyhydrogen steam generator for analysis.

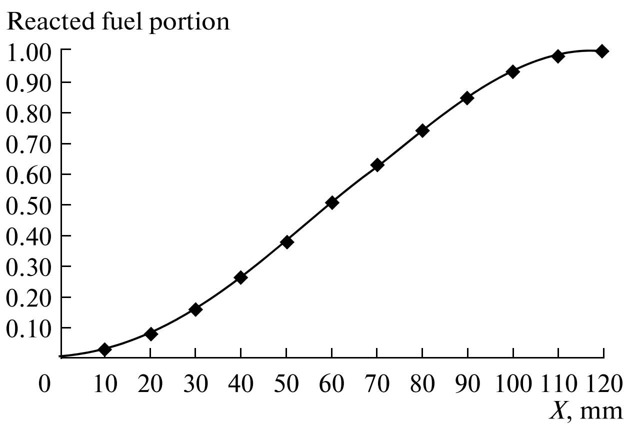

Fig. 6. Fuel combustion curve.

The curve of fuel combustion for the combustion chamber of the HSG can be represented in the form

$$\xi(x) = \left(\frac{x}{x_0}\right)^2 \left[3 - 2\frac{x}{x_0}\right]. \tag{1}$$

Here, $\xi(x)$ is the portion of the reacted fuel; x is the coordinate along the axis of the CC (distance from the injector head); x_0 is the distance at which the fuel conversion (combustion) in the flow core is completed, i.e., the extension of the mixing and combustion zone. It is evident that x_0 is substantially determined by the design of the mixing unit and injectors and angles of the incidence and divergence of the fuel and oxidizer jets.

All other things being the same, x_0 for coaxial mixing units takes maximum values; i.e., it can be used as the evaluation of x_0 from above. From the experience of experimental investigation of combustion chambers of the LRD operating on the oxygen–hydrogen or oxygen–methane fuel and having the mixing head with the coaxial mixing units, it was found that the extension x_0 for the zone of the mixing and combustion of fuel components in the flow core is of the order of 10–15 characteristic sizes of the mixing unit. The mixing unit of the combustion chamber of the flame unit of the oxyhydrogen steam generator has a characteristic size of 10–12 mm (distance between centers of fuel jet injectors). Thus, for the combustion chamber of the steam generator, as an upper estimate, $x_0 \approx 120$ mm can be taken. Figure 6 represents the curve of fuel combustion in the combustion chamber of the steam generator, which was calculated by formula (1) for the nominal mode (25 MW(t)).

From the shape of the combustion curve, it follows that significant heat generation begins in immediate proximity to the flame bottom of the mixing unit, and at the nominal power of the oxyhydrogen steam generator in 25 MW, the thermal power released during combustion of 50% hydrogen at a distance of 60 mm is 12.5 MW. This results in the appearance of great heat fluxes and the necessity of effective cooling of the mixing unit and walls of the CC. In the case of the use of mixing units with the impinging jets, the change in the angle of the incidence and the impulse of the fuel and oxidizer jets gives the possibility of the displacement of the zone of active combustion along the CC axis and the optimization of processes. In all cases in the CC gas recirculation appears [21]. Therefore, there is a need to eliminate the ingress of reverse-direction oxygen-enriched vortices on the hot flame wall. These problems are solved on the basis of experimental investigation by the optimization of the mutual arrangement of the fuel and oxidizer injectors at the injector head, by the change in the angles of incidence and the impulse of jets and the formation of the peripheral system of additional hydrogen injectors providing the presence of the reducing medium immediately at the flame wall.

The test results for H_2/O_2 steam generators with different types of mixing units showed that the mixing units with jet injectors with the jets impinging under the angle $\theta/2$ were the most effective because they provided for the optimum location and extension of the zone for active mixing and combustion in the CC and the formation of the reducing medium nearby at the flame wall [32]. The combustion product temperature at the outlet into the evaporation chamber is more than 3500 K, and their weight composition corresponds to 80% H_2O, 8% O_2, and 2% H_2. The reduction in the steam temperature in the evaporation chamber is realized mainly owing to mixing with water drops sprayed in the flow and their evaporation. The equilibrium composition of steam at a temperature less than 1900 K corresponds to 100% H_2O.

However, the equilibrium ideal process is unrealizable in practice, and the finite steam composition at

the steam generator outlet contains some amount of noncondensable gases, which depends on the rate of reduction in the combustion product temperature within the evaporation chamber (on the order of 10^5 K/s). The characteristic relaxation times for the composition in the $H_2/O_2/H_2O$ mixer at high temperatures are 10^{-6} s; however, they rise at $T \approx 2000$ K (the reaction rate decreases), and conditions for quenching the composition may occur.

EFFECTIVENESS OF STEAM GENERATION

The substantial distinction of H_2/O_2 steam generators from the LRE is the great weight fraction of the ballasting component, namely, water and steam, within the steam generated at the outlet, $g > 70\%$. The main steam mass is formed as a result of the mixing of water with the combustion product and its evaporation in the evaporation chamber. The heat losses from the flame unit are negligible because all water from the cooling system falls into the evaporation chamber. Therefore, the difference in the parameters of steam generated at the steam generator outlet from equilibrium conditions corresponding to complete combustion of fuel and ideal mixing is determined by the perfection of processes in the combustion and evaporation chambers, i.e., finally, by the total effects of quenching the composition [20].

The approximate evaluation of the completeness of fuel combustion can be obtained on the basis of the analysis of the composition of noncondensable gases in steam at the steam generator outlet, namely, hydrogen, oxygen, and purging nitrogen gas. The results of these measurements showed that the total content of noncondensable gases during operation in the basic mode was less than 2 vol % for mixing units with the jet injectors with the hydrogen and oxygen jets impinging under the angle $\theta/2$ and for the mixing units with the impinging jets and additional peripheral hydrogen injectors. The total content of noncondensable gases in steam at the outlet was more than 2 vol % with the use of the mixing unit with the coaxial injectors, which indicates the insufficient length of the combustion chamber in this case (Table 2).

The integral evaluation of the perfection of processes in the steam generator can be obtained as a result of comparison of the data of the temperature of steam generated with the equilibrium thermodynamic calculation at known flow consumptions of components and water in the cooling system and the evaporation chamber. Investigations carried out early in tests of the 10M H_2/O_2 steam generator with a thermal power up to 18 MW(t) with the coaxial jet injectors showed that the integral effectiveness of steam generation at the mass water portion $g \approx 0.7$ and the steam temperature $T_s \approx 1200$ K was $\varphi_{sg} \approx 0.95$ and decreased at the steam temperature $T_s \approx 600$ K to $\varphi_{sg} \approx 0.9$ as g increased from $g = 0.7$ to $g = 0.8$ [20, 21]. The minimum g corresponding to the maximum steam temperature T_s is determined by the minimum water consumption for cooling the combustion chamber, which is 1.9–2 kg/s at the nominal power for the steam generator of the 25M model ($g \approx 0.6$). The steam temperature is $T_s = 1900$ K and φ_{sg} is close to one. Figure 7 and Table 2 represent the basic results of experimental investigations for the effectiveness of steam generation in H_2/O_2 steam generators of the megawatt power class with various types of mixing units at different excess oxidizer coefficients by data from [20, 21] and results of the present work. One can conclude that there are admissible deviations of component composition at the combustion chamber inlet of the steam generator for providing its high thermodynamic effectiveness. The excess oxidizer coefficient should be in the range of $0.93 < \alpha < 1.05$ at $g \approx 0.7$. The parameters of steam generated under these conditions are close to equilibrium thermodynamic ones, and the total concentration of unburnt noncondensable gases in steam is no greater than 2 vol%.

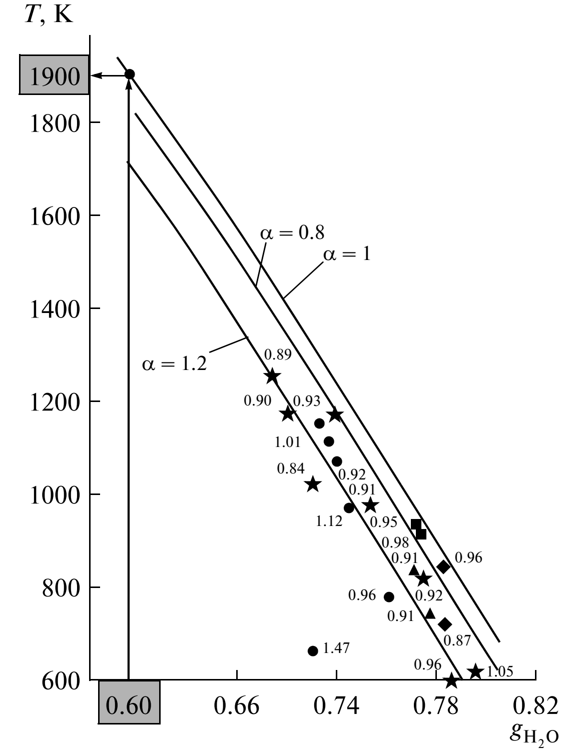

Fig. 7. Steam temperature vs. mass water portion at different excess oxidizer coefficients.

DYNAMIC CHARACTERISTICS OF H_2/O_2 STEAM GENERATORS

The operation mode of the oxyhydrogen steam generator is practically independent of the type of mixing unit; only limited variation in the temperature of steam generated occurs depending on the completeness of hydrogen combustion. Figure 8 shows the

Table 2. Main findings of experimental investigations of the steam generation effectiveness in H_2/O_2 steam generators of the megawatt power class with different types of mixing units for different excess oxidizer coefficients

	Mixing unit with jet injectors with the hydrogen and oxygen jets impinging under an angle 30°	Mixing unit with jet injectors with the hydrogen and oxygen jets impinging under an angle 15°	Mixing unit with the coaxial-jets injectors	Mixing unit with jet injectors with the hydrogen and oxygen jets impinging under the angle of 15° with the additional hydrogen injectors
Volume hydrogen content, %	no data	0.27	3.17	0.37
Volume oxygen content, %	no data	1.07	1.83	1.25
Excess oxidizer coefficient	0.91	0.93	0.95	0.91
Notation	[30]	[32]	[33]	[32]

typical change in the temperature and pressure of steam generated in the second mixing chamber during tests, from which it is evident that the access of the oxyhydrogen steam generator to the basic mode with a thermal power of 23–25 MW at the soft starting occurs in the following three steps.

(i) From 0 to 4 s, the starting and beginning of the operation of the flame igniter forming the heating of the combustion chamber occur, its temperature attains 600–700 K; from 2 s, the cooling system of the starting mode is engaged as a result of which a fall in temperature to 325 K in the mixing chamber occurs.

(ii) From 4 s, the starting flow consumptions of hydrogen and oxygen feed as a result of which the temperature of steam generated rises to 500–550 K, and at the same time the heating of the oxyhydrogen steam generator and the diagnosis of the basic check parameters are realized.

(iii) From 6 s, the main flow consumptions of hydrogen, oxygen, and water feed; to 8–10 s, the temperature of steam generated increases to that designed, and the oxyhydrogen steam generator attains a designed power of 23–25 MW.

Thus, the time of the access of the oxyhydrogen steam generator to the basic mode under a soft start is less than 10 s. Investigations of the DLR [7, 8, 12] showed that as the starting mode is excluded from starting, the time of access to the basic mode can be shortened to 3–5 s. The small time of the starting of similar sets significantly enlarges the field of their application in power engineering as the emergency and standby power supplies.

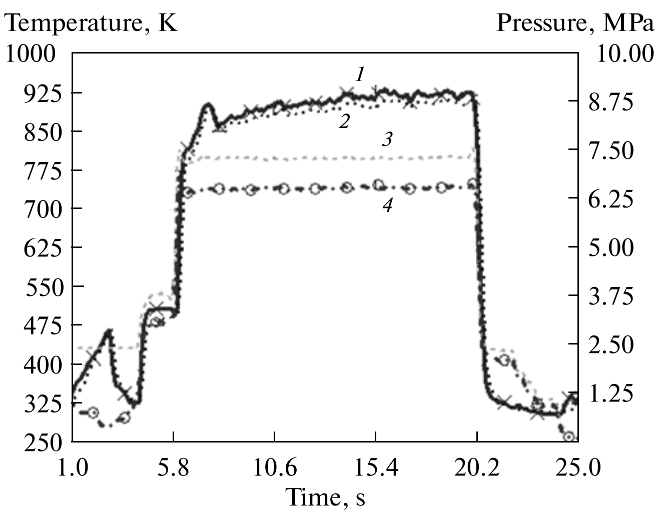

Fig. 8. Typical variation in the temperature and pressure of steam generated in the second mixing chamber during tests: *1* steam temperature in the center of the mixing chamber, *2* steam temperature at the wall of the mixing chamber, *3* steam pressure in the combustion chamber, *4* steam pressure in the mixing chamber.

CONCLUSIONS

The experimental investigations showed that the use of mixing units with the impinging jets of fuel and oxidizer at the optimization of angles of the incidence and jet impulses and at the minimization of the feed of reaction products, namely, water and steam, into the combustion chamber due to the use of the combined system of the internal and external cooling of the CC allow one to minimize the effects of quenching the components and provide for the high completeness of fuel combustion in H_2/O_2 steam generators of the megawatt power class.

The dynamic characteristics of the steam generator provide the attainment of the nominal power in less than 10 s, and in this respect the steam generators developed on the basis of the LRE technology are beyond comparison.

With allowance made for the high parameters of steam generated, good dynamical characteristics, and small production costs, such sets may have wide application as compact sources of high-temperature steam

in the technology of processing natural fuels and biomass for energy engineering and other fields of the national economy, such as the following:

(i) in enterprises having hydrogen as a by-product for realizing autonomous systems for the accumulation and production of thermal and electric energy;

(ii) in realizing hydrogen systems for electric power accumulation and compensation of load curve unevenness for NPPs, coal SPPs, and energy plants with renewable energy sources with a recuperation coefficient of no less than 50% in the power range from 0.1 to 100 MW.

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